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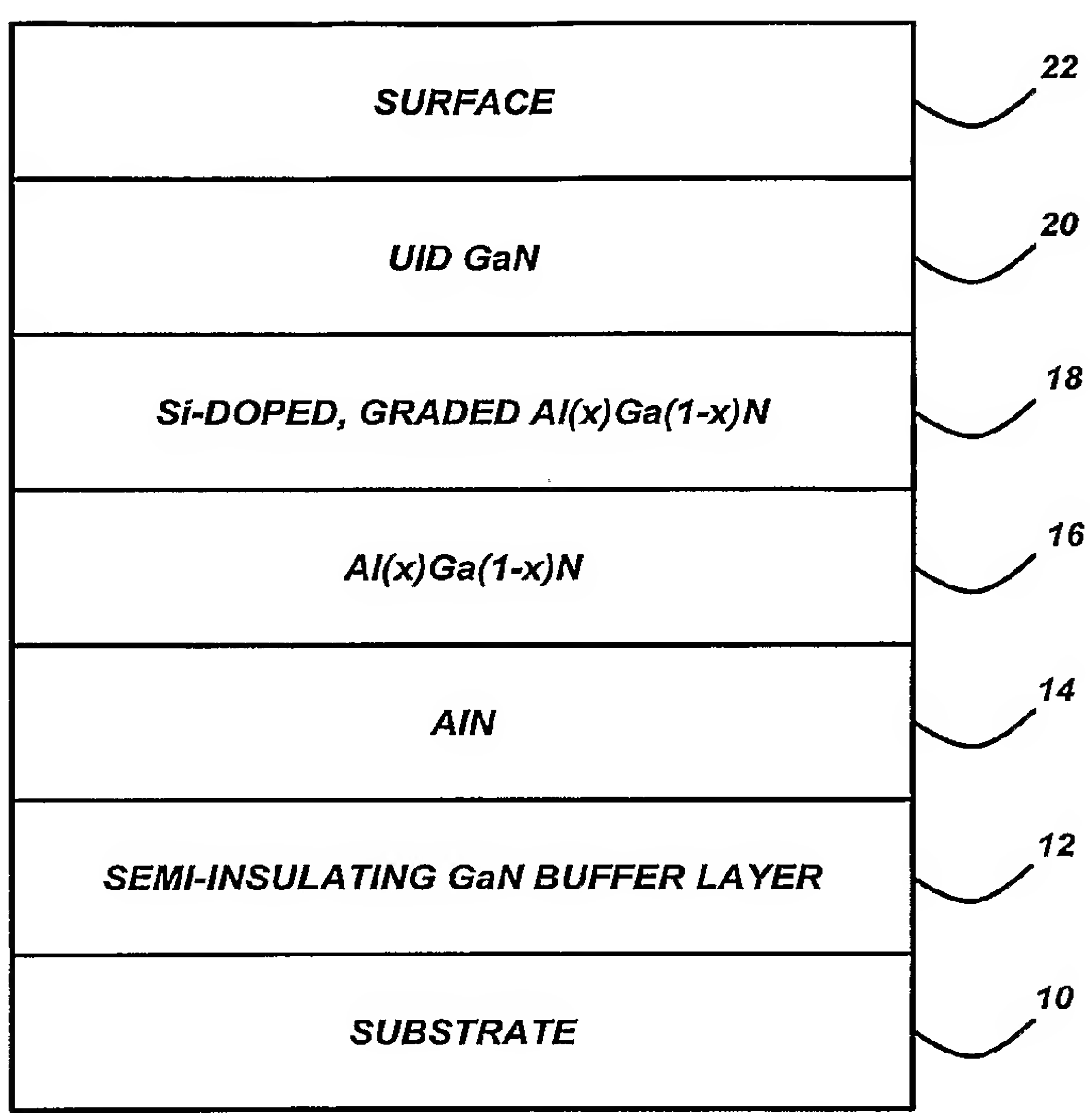
(54) Title: GaN/AlGaN/GaN DISPERSION-FREE HIGH ELECTRON MOBILITY TRANSISTORS



(57) Abstract: A dispersion-free high electron mobility transistor (HEMT), comprised of a substrate; a semi-insulating buffer layer, comprised of gallium nitride (GaN) or aluminum gallium nitride (A1GaN), deposited on the substrate, an A1GaN barrier layer, with an aluminum (Al) mole fraction larger than that of the semi-insulating buffer layer, deposited on the semi-insulating buffer layer, an n-type doped graded A1GaN layer deposited on the A1GaN barrier layer, wherein an Al mole fraction is decreased from a bottom of the n-type doped graded A1GaN layer to a top of the n-type doped graded A1GaN layer, and a cap layer, comprised of GaN or A1GaN with an Al mole fraction smaller than that of the A1GaN barrier layer, deposited on the n-type doped graded A1GaN layer.

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GaN/AlGaN/GaN DISPERSION-FREE HIGH ELECTRON MOBILITY TRANSISTORS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit under 35 U.S.C. §119(e) of the following co-pending and commonly-assigned United States Provisional Patent Application:

Serial No. 60/510,695, entitled "GaN/AlGaN/GaN dispersion-free high electron mobility transistors," filed on October 10, 2003, by Likun Shen, Sten J. Heikman and Umesh K. Mishra, attorneys docket number 30794.107-US-P1; which application is incorporated by reference herein.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

This invention was made with Government support under Grant No. N00014-01-1-0764 awarded by the CANE MURI program. The Government has certain rights in this invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention.

This invention relates to semiconductor devices, and more particularly, to gallium nitride/aluminum gallium nitride/gallium nitride (GaN/AlGaN/GaN) dispersion-free high electron mobility transistors (HEMTs).

2. Description of the Related Art.

GaN power HEMTs suffer from "DC-to-RF dispersion," which is defined as the difference between the static and dynamic (e.g. gate lag measurement) I-V characteristics. This dispersion has been reported to be due to the slow response of the surface traps. In the prior art, silicon nitride (SiN) passivation has been used to suppress this problem, but the drawback of SiN passivation is that it is very sensitive to both surface and deposition conditions, which leads to poor reproducibility.

What is needed, then, are improved methods of fabricating dispersion-free GaN-based HEMTs without SiN passivation.

SUMMARY OF THE INVENTION

To overcome the limitations in the prior art described above, and to overcome other limitations that will become apparent upon reading and understanding the present specification, the present invention discloses a dispersion-free high electron mobility transistor (HEMT), comprised of a substrate; a semi-insulating buffer layer, comprised of gallium nitride (GaN) or aluminum gallium nitride (AlGaN), deposited on the substrate, an AlGaN barrier layer, with an aluminum (Al) mole fraction larger than that of the semi-insulating buffer layer, deposited on the semi-insulating buffer layer, an n-type doped graded AlGaN layer deposited on the AlGaN barrier layer, wherein an Al mole fraction is decreased from a bottom of the n-type doped graded AlGaN layer to a top of the n-type doped graded AlGaN layer, and a cap layer, comprised of GaN or AlGaN with an Al mole fraction smaller than that of the AlGaN barrier layer, deposited on the n-type doped graded AlGaN layer.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring now to the drawings in which like reference numbers represent corresponding parts throughout:

FIG. 1 is a schematic cross-section of a GaN/AlGaN/GaN HEMT;

FIG. 2 is a graph that illustrates sheet charge density vs. surface potential of a GaN/AlGaN/GaN HEMT with a 250 nm GaN cap;

FIG. 3 is a schematic cross-section of a GaN/AlGaN/GaN HEMT;

FIG.4A is a schematic cross-section of a GaN/AlGaN/GaN HEMT;

FIG. 4B is a graph that illustrates a band diagram of a GaN/AlGaN/GaN HEMT;

FIG. 5 is a graph that illustrates DC and Pulsed I-V curves;

FIG. 6 is a graph that illustrates power performance at 8 GHz of 15 V drain bias; and

FIG. 7 is a flowchart that illustrates the steps for fabricating a dispersion-free HEMT, according to the preferred embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

In the following description of the preferred embodiment, reference is made to the accompanying drawings which form a part hereof, and in which is shown by way of illustration a specific embodiment in which the invention may be practiced. It is to be understood that other embodiments may be utilized and structural changes may be made without departing from the scope of the present invention.

General Description

The present invention uses an epitaxial solution to suppress the "DC-to-RF" dispersion problem suffered by GaN power HEMTs. This epitaxial solution results in the novel epitaxial structure of a GaN/AlGaN/GaN HEMT shown in FIG. 1, comprising a sapphire or silicon carbide (SiC) substrate 10, semi-insulating (S.I.) GaN buffer layer 12, AlN layer 14, $Al_xGa_{1-x}N$ layer 16, silicon-doped (Si-doped), graded $Al_xGa_{1-x}N$ layer 18, GaN cap 20 and surface 22.

In this structure, the GaN cap 20 is unintentionally doped (UID). The amount of dispersion depends on a ratio of a pinch-off voltage between the gate and access regions, wherein the pinch-off voltage is proportional to the distance between the channel and surface. Therefore, the GaN cap 20 needs to be a certain thickness to decrease dispersion to an acceptable level. For example, if dispersion needs to be less than 10 %, the thickness of the GaN cap 20, therefore, should be at least 10 times as thick as the distance between the channel and metal gate.

The thickness of the Si-doped, graded AlGaN layer 18 is around 5-40 nm. The Al mole fraction varies linearly from 0 at the GaN 20 / graded AlGaN 18 interface to the mole fraction of the adjacent AlGaN layer 16 at the graded AlGaN 18 / AlGaN 16

interface . This layer 18 is uniformly doped by Si and doping density can be from 10 % to 100 % of the net polarization charge present in the graded AlGaN layer 18. The thickness of the AlGaN layer 16 is about 5-40 nm and the Al mole fraction can vary from a low of 5-10 % to a high of 70-90 %. The AlN layer 14 is 0.5-1 nm thick. The GaN buffer layer 12 is semi-insulating and 2-4 μm thick. The substrate 10 can be either sapphire or SiC.

Research has shown that the dispersion is caused by the slow response of the surface states at the drain access region. In order to decrease this effect, one solution is to increase the distance between the surface and channel so that the capacitance can be reduced. The ability of the surface states to modulate the channel decreases when this capacitance becomes smaller. Therefore, the thick GaN cap 20 in the access region reduces surface potential fluctuations from affecting device performance.

FIG. 2 illustrates sheet charge density vs. surface potential of the GaN/AlGaN/GaN HEMT with a 250 nm GaN cap. It can be seen that the channel is not depleted until -80 V, which is much larger than that of conventional AlGaN/GaN HEMT (about -10 V). This is the key element in the present invention to implement dispersion-free GaN HEMTs. The Si-doping of the graded AlGaN layer 18 is used to remove hole accumulation in said graded layer. A thin AlN layer is inserted to improve mobility.

The processing is similar to that of conventional HEMTs, except that deep etching is necessary for both the source/drain contact and gate, in order to obtain ohmic contacts, reasonable transconductance and pinch-off voltage.

FIG. 3 is a schematic cross-section of a GaN/AlGaN/GaN HEMT. This figure illustrates source (S) 24, drain (D) 26 and gate (G) 28 contacts, GaN layer 30, Si-doped, graded AlGaN layer 32, AlGaN layer 34 and semi-insulating (S.I.) GaN layer 36.

One sample with this structure was grown and fabricated. FIG.4A shows the details of the epitaxial structure and FIG. 4B shows the band diagram of a GaN/AlGaN/GaN HEMT.

The DC and gate lag pulsed I-V characteristics of the unpassivated sample were measured. No dispersion was observed up to 200 ns, as shown in FIG. 5. At 200 ns, current density of 1.25 A/mm and transconductance of 230 mS/mm were obtained. Small signal RF performance showed 22 GHz f_t and 40 GHz f_{max} for 0.7 μm-gate-length device. Power measurement of the unpassivated sample at 8 GHz showed 2 W/mm and 3 W/mm with a PAE (power added efficiency) of 42 % and 38 % at a drain bias of 10 V and 15 V, respectively, as shown in FIG. 6. This indicates that the dispersion is suppressed even in the GHz range.

Process Steps

FIG. 7 is a flowchart that illustrates the steps for fabricating a dispersion-free HEMT, according to the preferred embodiment of the present invention.

Block 38 represents depositing a semi-insulating buffer layer, comprised of gallium nitride (GaN) or aluminum gallium nitride (AlGaN), on a substrate, wherein the substrate is sapphire or silicon carbide.

Block 40 represents depositing an AlGaN barrier layer, with an aluminum (Al) mole fraction larger than that of the semi-insulating buffer layer, on the semi-insulating buffer layer. Note that this Block may also place a thin aluminum nitride (AlN) layer between the semi-insulating buffer layer and the AlGaN barrier layer.

Block 42 represents depositing an n-type doped graded AlGaN layer on the AlGaN barrier layer, wherein the Al mole fraction is decreased from the bottom of the layer to the top of the layer. Specifically, the Al mole fraction in the n-type doped graded AlGaN layer is varied through the layer, such that the Al mole fraction in the n-type doped graded AlGaN layer next to the AlGaN barrier layer equals the Al mole fraction of the AlGaN barrier layer, and that the Al mole fraction in the n-type doped graded AlGaN layer next to the cap layer equals the Al mole fraction of the cap layer.

Block 44 represents depositing a cap layer, comprised of GaN or AlGaN with an Al mole fraction smaller than that of the AlGaN barrier layer, on the n-type doped graded AlGaN layer. As a result of this Block, the cap layer and the n-type doped

graded AlGaN layer separate a channel from the HEMT's surface in an access region to minimize surface potential fluctuations from affecting device performance. Moreover, the n-type doped graded AlGaN layer prevents hole accumulation at an interface between the cap layer and the AlGaN barrier layer.

Possible Modifications

Possible modifications include:

1. The structure has a low Al mole fraction AlGaN cap layer instead of GaN cap layer.
2. The graded AlGaN region is removed, thus there is abrupt GaN/AlGaN interface, instead of a graded junction.
3. The n-type doping is performed with other shallow donor element than Si.
4. The graded AlGaN layer has a non-linear change in Al composition over a distance.
5. Part/parts of the distance during which the Al composition is changed are undoped.
6. The n-type doping in the graded AlGaN region is not uniform.
7. One or more parts of the UID GaN cap are doped by n-type or p-type dopants.
8. Instead of a plain GaN cap, there can be another heterojunction (e.g. AlGaN/GaN to form another 2DEG channel) to screen surface potential fluctuation further.
9. The GaN cap and the graded AlGaN layer can be replaced by a thick, graded AlGaN layer, wherein the thickness of the graded AlGaN is similar to the thickness of the GaN cap, to screen the surface potential fluctuation.

CONCLUSION

This concludes the description of the preferred embodiment of the present invention. The foregoing description of one or more embodiments of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. It is intended that the scope of the invention be limited not by this detailed description, but rather by the claims appended hereto.

WHAT IS CLAIMED IS:

1. A dispersion-free high electron mobility transistor (HEMT), comprising:

a substrate;

a semi-insulating buffer layer, comprised of gallium nitride (GaN) or aluminum gallium nitride (AlGaN), deposited on the substrate;

an AlGaN barrier layer, with an aluminum (Al) mole fraction larger than that of the semi-insulating buffer layer, deposited on the semi-insulating buffer layer;

an n-type doped graded AlGaN layer deposited on the AlGaN barrier layer, wherein an Al mole fraction is decreased from a bottom of the n-type doped graded AlGaN layer to a top of the n-type doped graded AlGaN layer; and

a cap layer, comprised of GaN or AlGaN with an Al mole fraction smaller than that of the AlGaN barrier layer, deposited on the n-type doped graded AlGaN layer.

2. The dispersion-free HEMT of claim 1, wherein the cap layer and the n-type doped graded AlGaN layer separate a channel from the HEMT's surface in an access region to minimize surface potential fluctuations from affecting device performance.

3. The dispersion-free HEMT of claim 1, wherein the n-type doped graded AlGaN layer prevents hole accumulation at an interface between the cap layer and the AlGaN barrier layer.

4. The dispersion-free HEMT of claim 1, wherein the Al mole fraction in the n-type doped graded AlGaN layer is varied through the layer, such that the Al mole fraction in the graded layer next to the AlGaN barrier layer equals the Al mole fraction of the AlGaN barrier layer, and that the Al mole fraction in the n-type doped graded AlGaN layer next to the cap layer equals the Al mole fraction of the cap layer.

5. The dispersion-free HEMT of claim 1, wherein the substrate is sapphire or silicon carbide.

6. The dispersion-free HEMT of claim 1, wherein a thin aluminum nitride (AlN) layer is placed between the semi-insulating buffer layer and the AlGaN barrier layer.

7. A method of fabricating a dispersion-free high electron mobility transistor (HEMT), comprising:

depositing a semi-insulating buffer layer, comprised of gallium nitride (GaN) or aluminum gallium nitride (AlGaN), on a substrate;

depositing an AlGaN barrier layer, with an aluminum (Al) mole fraction larger than that of the semi-insulating buffer layer, on the semi-insulating buffer layer;

depositing an n-type doped graded AlGaN layer on the AlGaN barrier layer, wherein the Al mole fraction is decreased from the bottom of the layer to the top of the layer; and

depositing a cap layer, comprised of GaN or AlGaN with an Al mole fraction smaller than that of the AlGaN barrier layer, on the n-type doped graded AlGaN layer.

8. The method of claim 7, wherein the cap layer and the n-type doped graded AlGaN layer separate a channel from the HEMT's surface in an access region to minimize surface potential fluctuations from affecting device performance.

9. The method of claim 7, wherein the n-type doped graded AlGaN layer prevents hole accumulation at an interface between the cap layer and the AlGaN barrier layer.

10. The method of claim 7, wherein the Al mole fraction in the n-type doped graded AlGaN layer is varied through the layer, such that the Al mole fraction in the n-type doped graded AlGaN layer next to the AlGaN barrier layer equals the Al mole fraction of the AlGaN barrier layer, and that the Al mole fraction in the n-type doped graded AlGaN layer next to the cap layer equals the Al mole fraction of the cap layer.

11. The method of claim 7, wherein the substrate is sapphire or silicon carbide.

12. The method of claim 7, wherein a thin aluminum nitride (AlN) layer is placed between the semi-insulating buffer layer and the AlGaN barrier layer.

13. A dispersion-free high electron mobility transistor (HEMT), comprising:

a substrate;

a semi-insulating buffer layer, comprised of gallium nitride (GaN) or aluminum gallium nitride (AlGaN), deposited on the substrate;

an AlGaN barrier layer, with an aluminum (Al) mole fraction larger than that of the semi-insulating buffer layer, deposited on the semi-insulating buffer layer; and

an n-type doped graded AlGaN layer deposited on the AlGaN barrier layer, wherein the aluminum mole fraction is decreased from the bottom of the layer to the top of the layer.

14. The dispersion-free HEMT of claim 13, wherein the n-type doped graded AlGaN layer separates a channel from the HEMT's surface in an access region to minimize surface potential fluctuations from affecting device performance.

15. The dispersion-free HEMT of claim 13, wherein the n-type doping of the n-type doped graded AlGaN layer prevents hole accumulation in the n-type doped graded AlGaN layer or in the AlGaN barrier layer.

16. The dispersion-free HEMT of claim 13, wherein the Al mole fraction in the n-type doped graded AlGaN layer is varied through the n-type doped graded AlGaN layer, such that the Al mole fraction in the n-type doped graded AlGaN layer next to the AlGaN barrier layer equals the Al mole fraction of the AlGaN barrier layer, and that the Al mole fraction at the top of the n-type doped graded AlGaN layer is less than 0.10.

17. The dispersion-free HEMT of claim 13, wherein the substrate is sapphire or silicon carbide.

18. The dispersion-free HEMT of claim 13, wherein a thin aluminum nitride (AlN) layer is placed between the semi-insulating buffer layer and the AlGaN barrier layer.

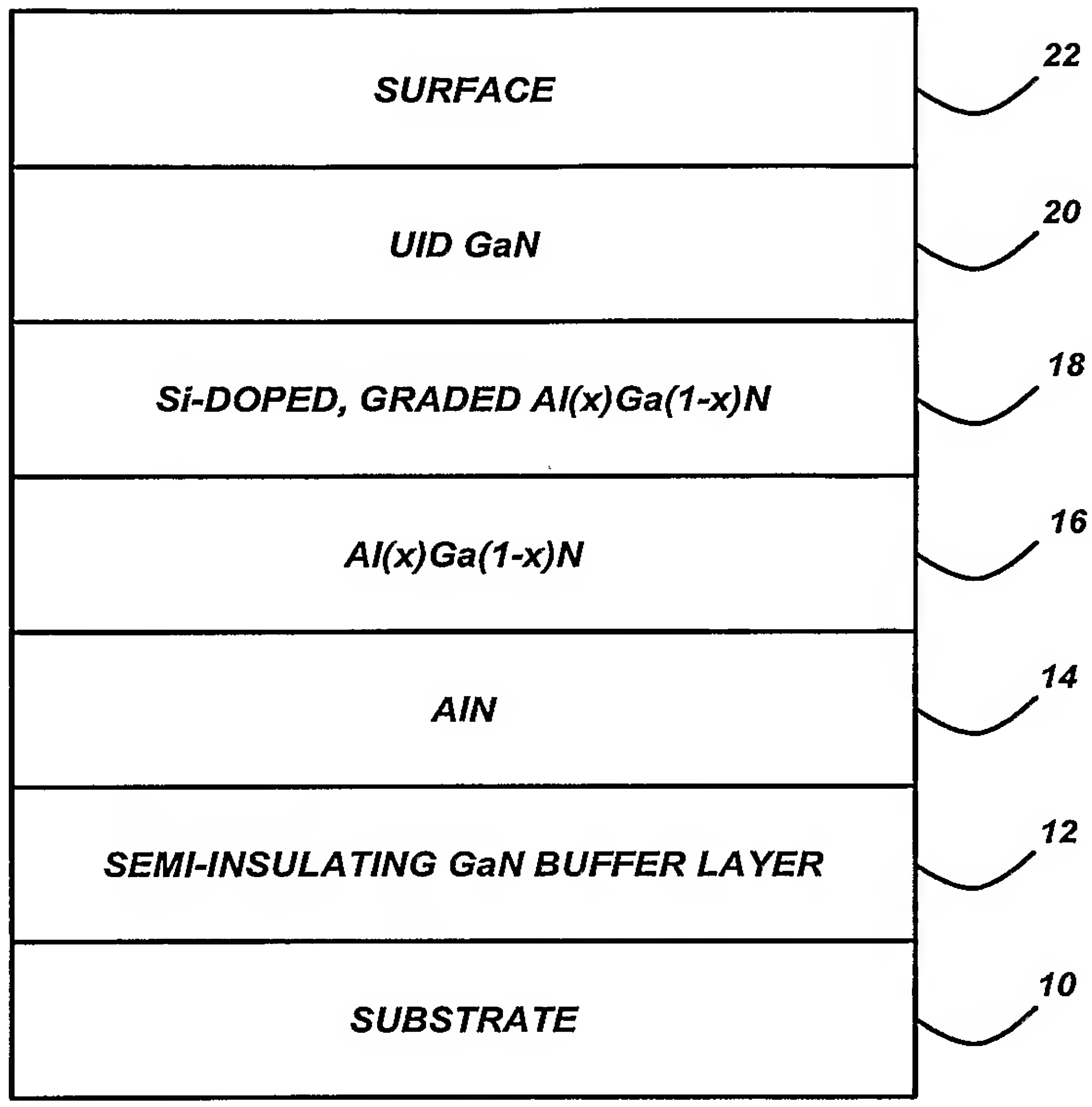

SURFACE
22
UID GaN
20
Si-DOPED, GRADED Al(x)Ga(1-x)N
18
Al(x)Ga(1-x)N
16
AlN
14
SEMI-INSULATING GaN BUFFER LAYER
12
SUBSTRATE
10

FIG. 1

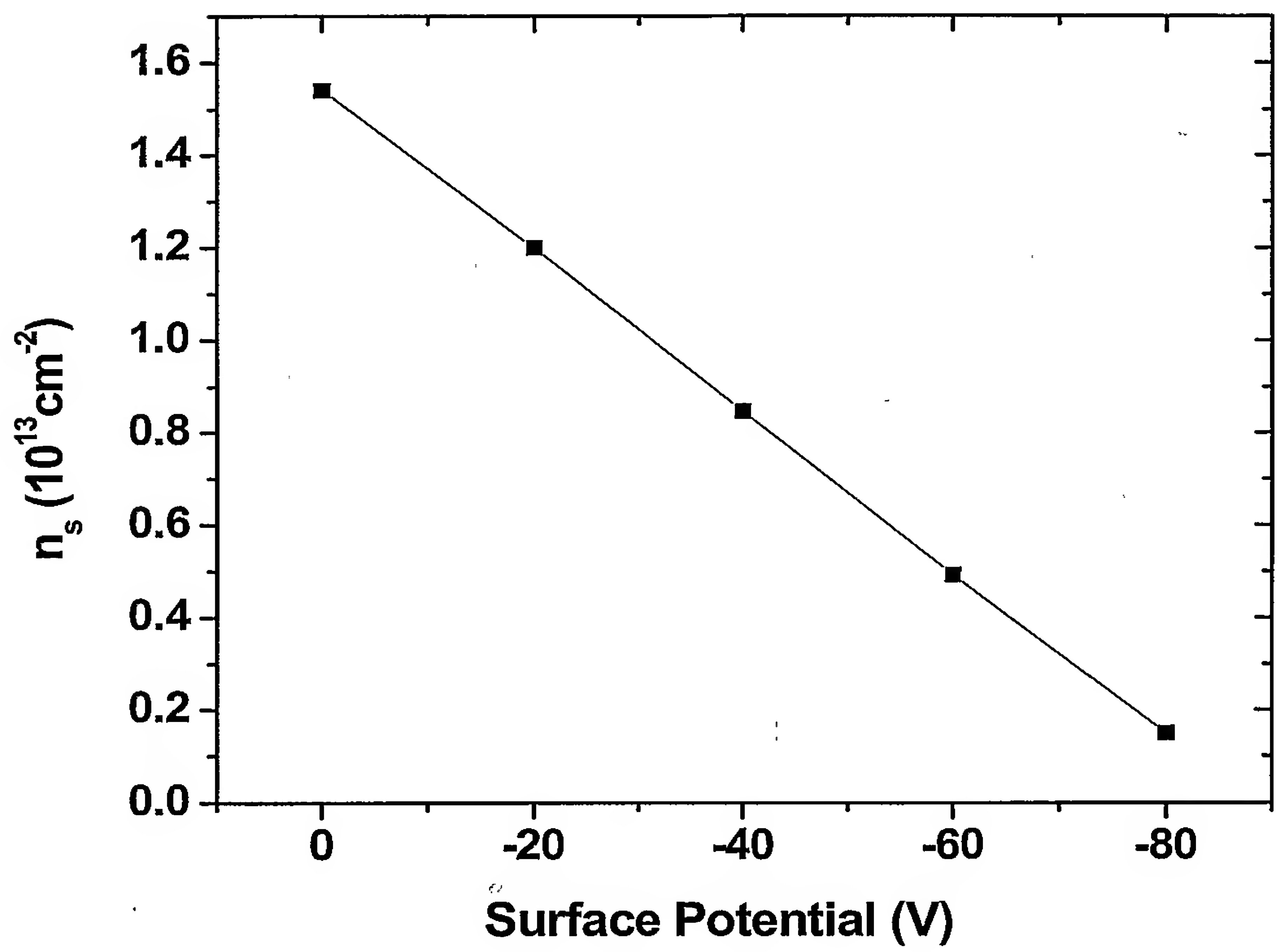

1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
n_s (10^{13}cm^{-2})
0
-20
-40
-60
-80
Surface Potential (V)

FIG. 2

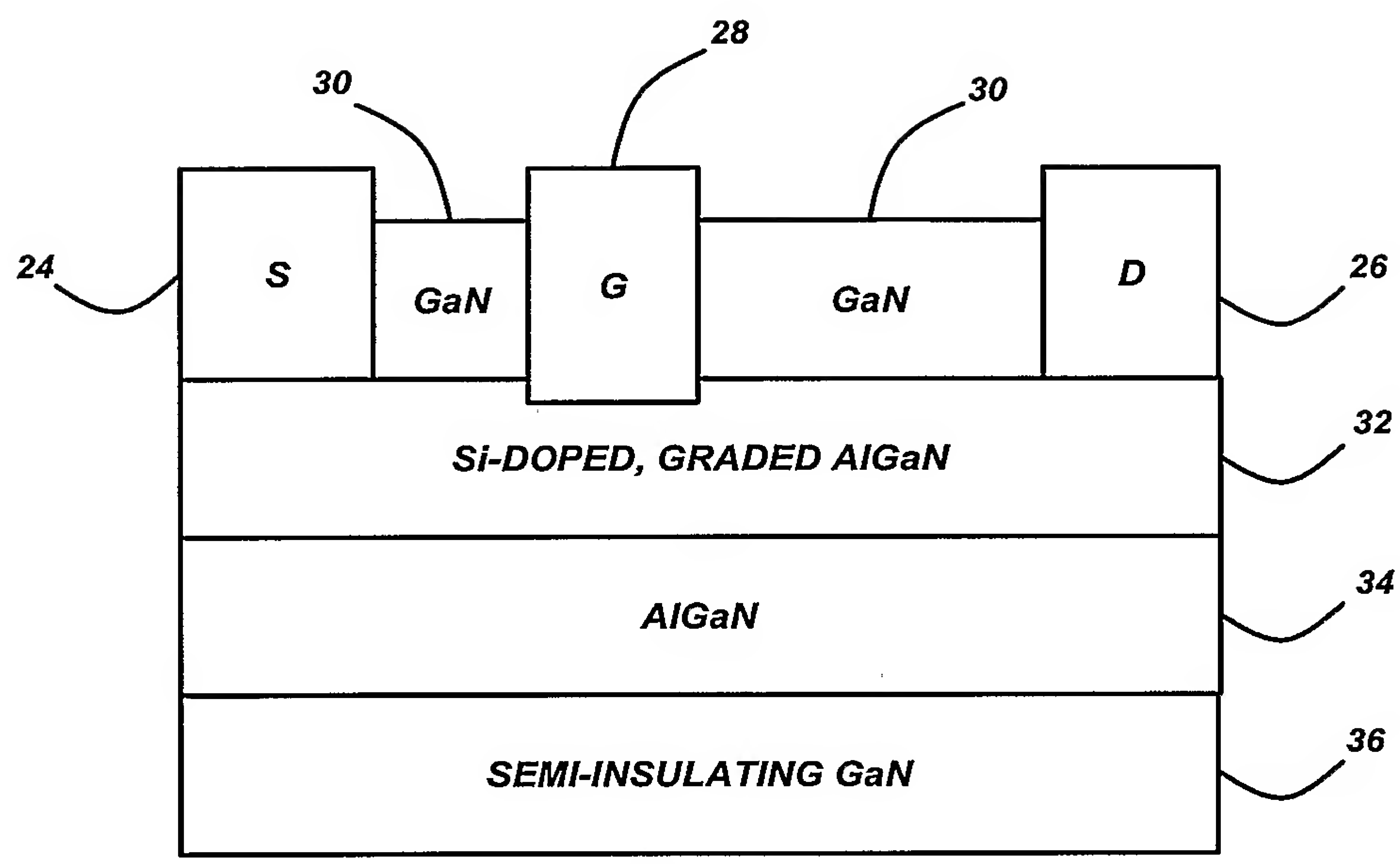

28
30
30
24
S
GaN
G
GaN
D
26
Si-DOPED, GRADED AlGaN
32
AlGaN
34
SEMI-INSULATING GaN
36

FIG. 3

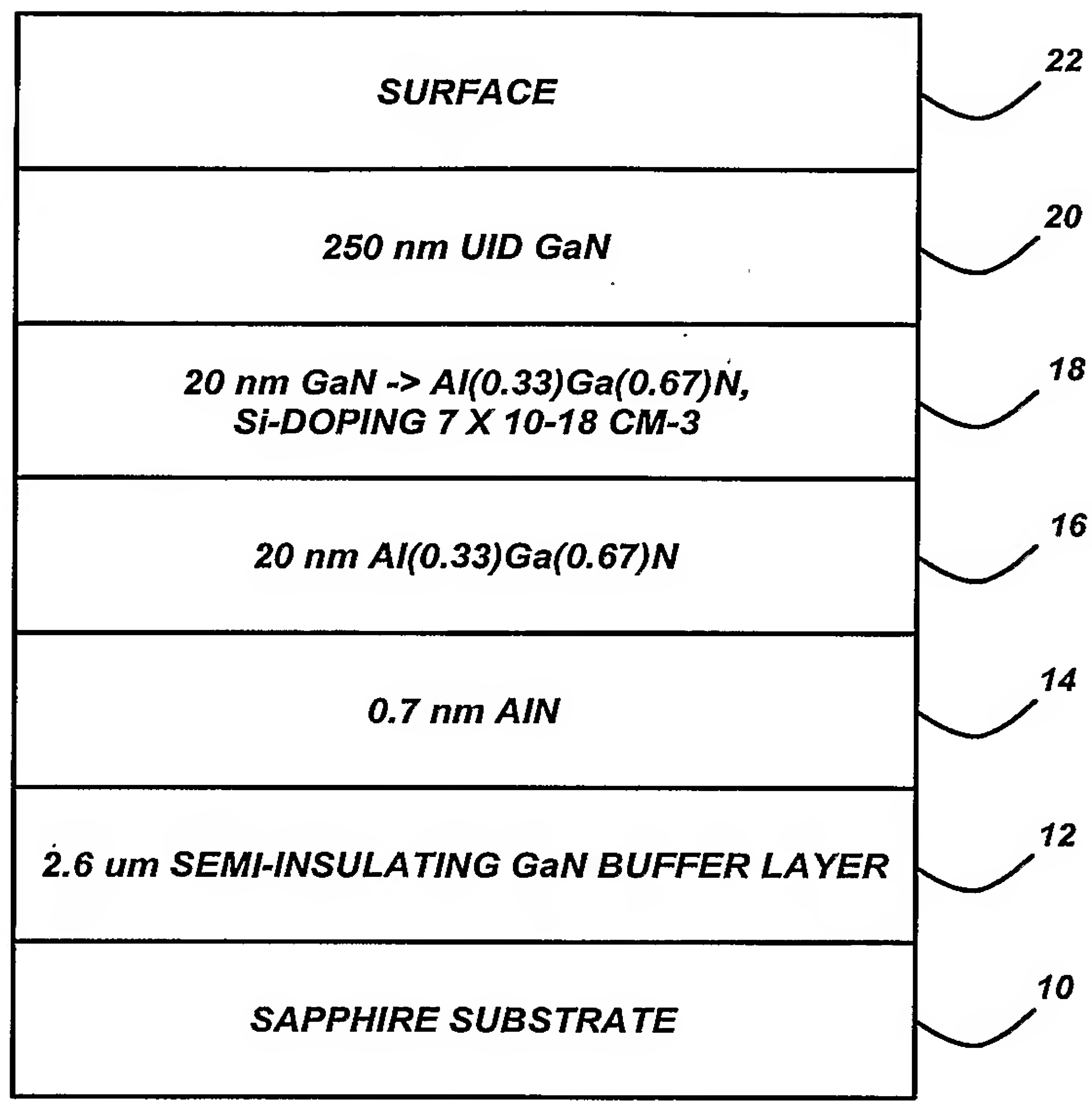
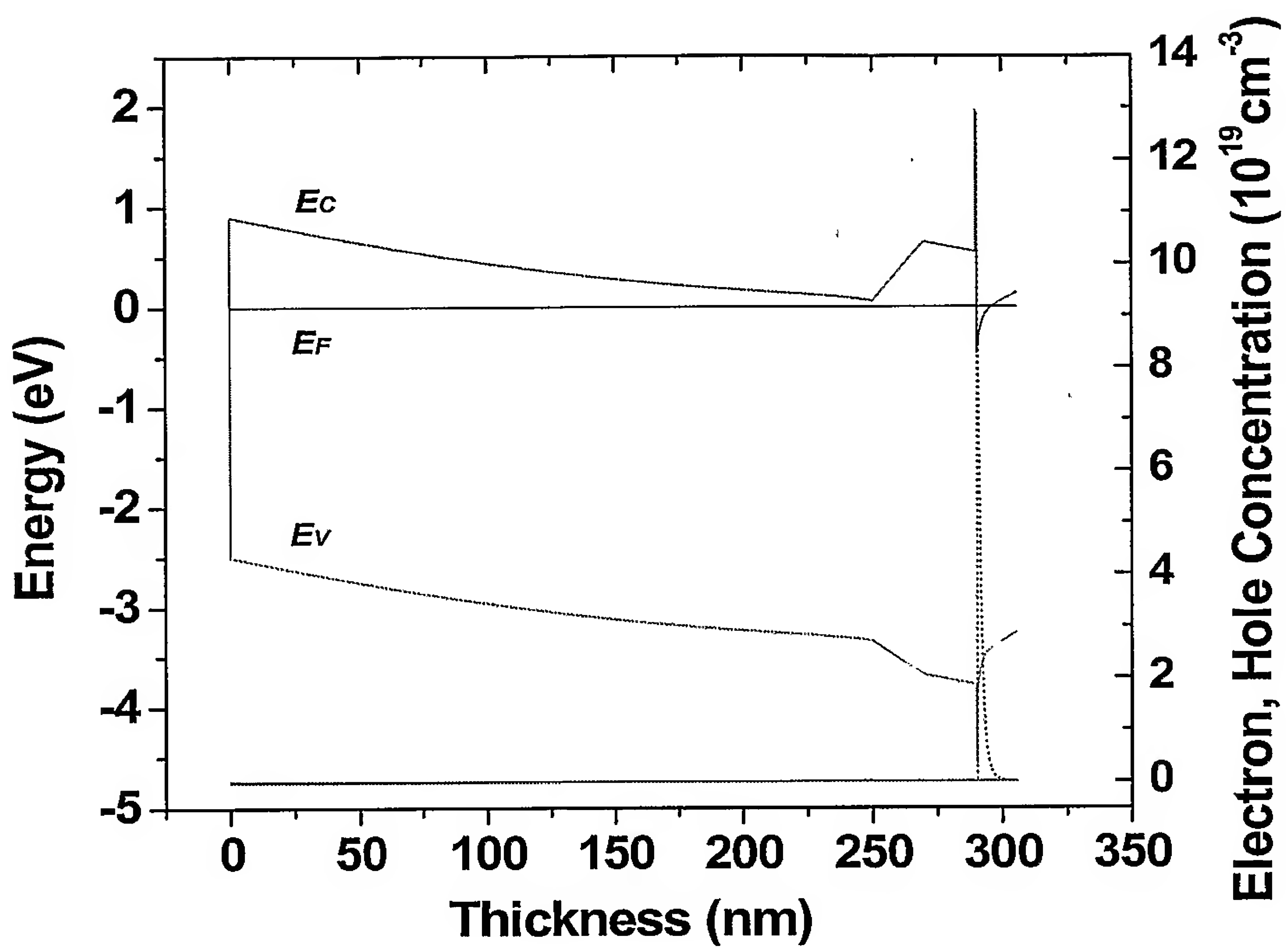
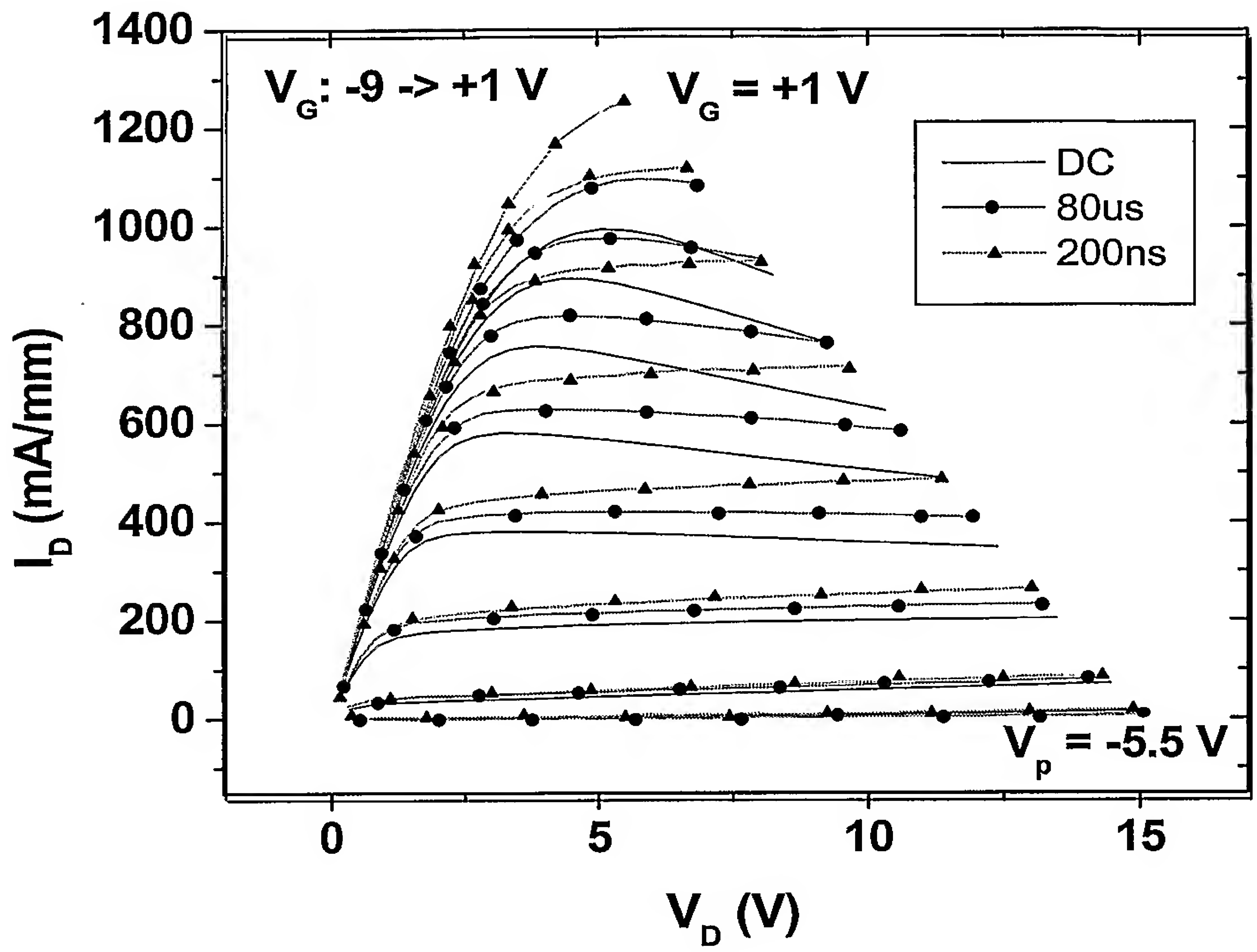

SURFACE
22
250 nm UID GaN
20
20 nm GaN -> Al(0.33)Ga(0.67)N,
Si-DOPING 7 X 10-18 CM-3
18
20 nm Al(0.33)Ga(0.67)N
16
0.7 nm AlN
14
2.6 um SEMI-INSULATING GaN BUFFER LAYER
12
SAPPHIRE SUBSTRATE
10

FIG. 4A



Ec
EF
Ev
Energy (eV)
Thickness (nm)
Electron, Hole Concentration ($10^{19}cm^{-3}$)
2
1
0
-1
-2
-3
-4
-5
0
50
100
150
200
250
300
350
14
12
10
8
6
4
2
0

FIG. 4B



1400
1200
1000
800
600
400
200
0
I_D (mA/mm)
V_G: -9 -> +1 V
V_G = +1 V
DC
80us
200ns
V_p = -5.5 V
0
5
10
15
V_D (V)

FIG. 5

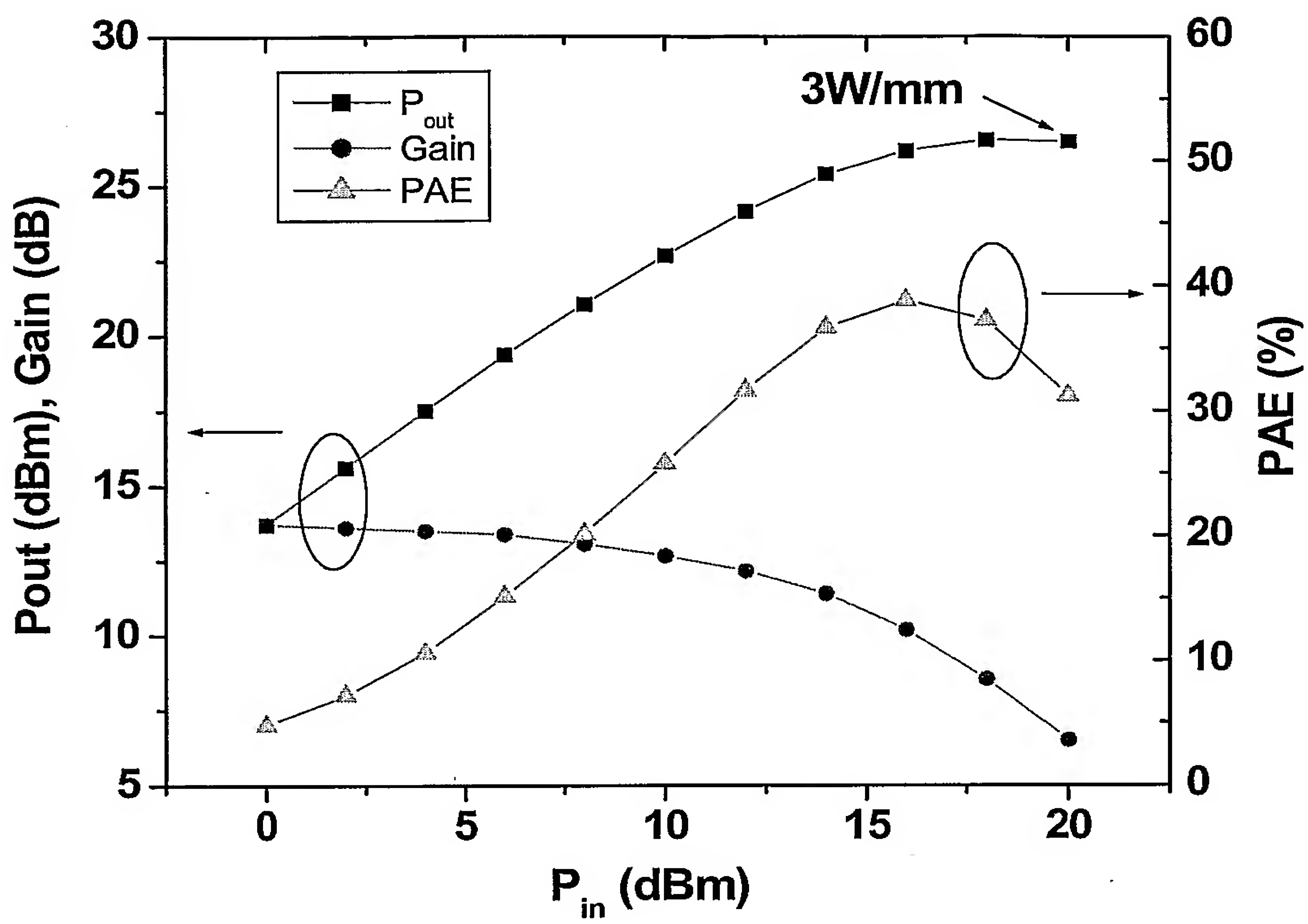

P_out
Gain
PAE
3W/mm
Pout (dBm), Gain (dB)
PAE (%)
P_in (dBm)
30
25
20
15
10
5
60
50
40
30
20
10
0
0
5
10
15
20

FIG. 6

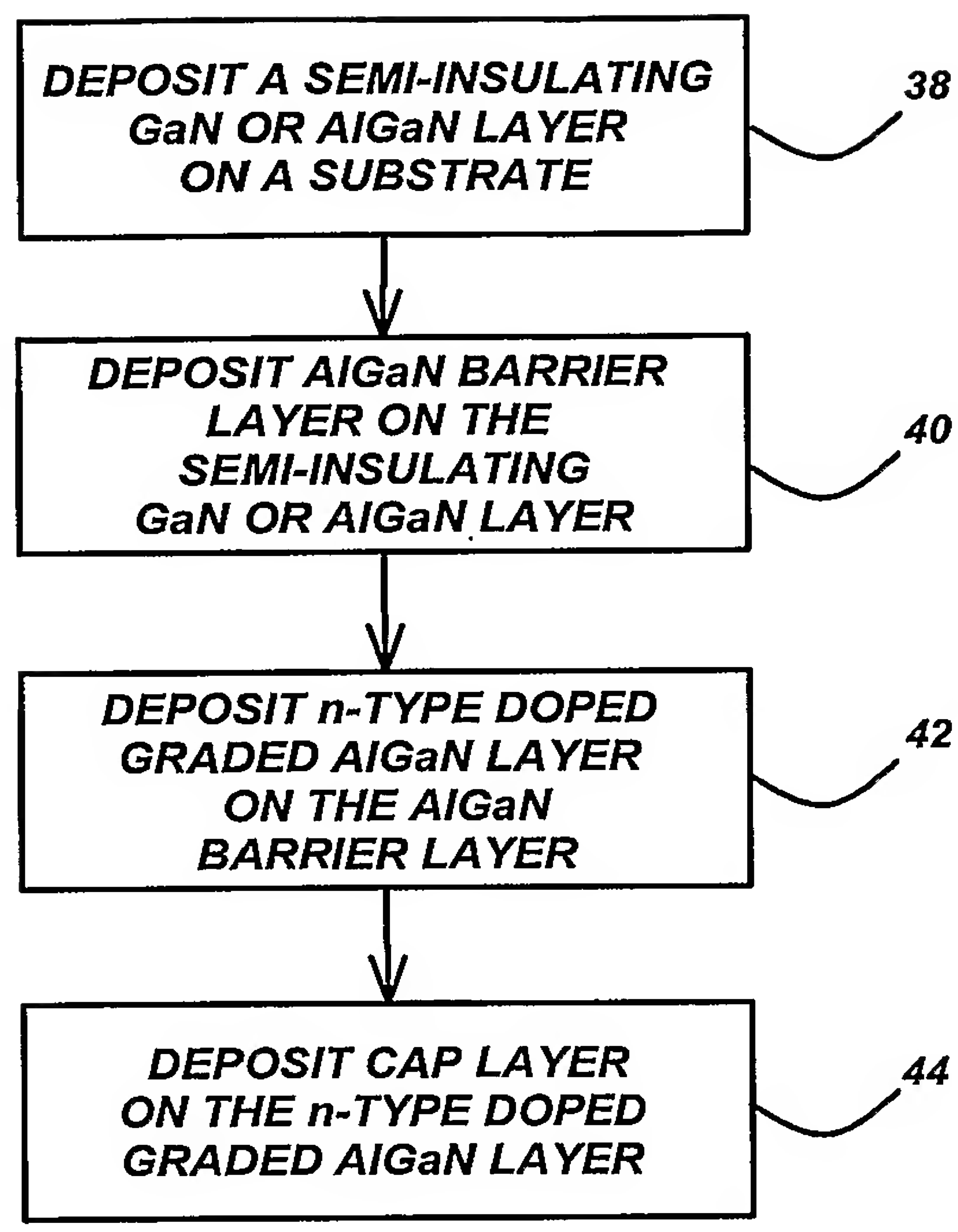

DEPOSIT A SEMI-INSULATING GaN OR AlGaN LAYER ON A SUBSTRATE
38
DEPOSIT AlGaN BARRIER LAYER ON THE SEMI-INSULATING GaN OR AlGaN LAYER
40
DEPOSIT n-TYPE DOPED GRADED AlGaN LAYER ON THE AlGaN BARRIER LAYER
42
DEPOSIT CAP LAYER ON THE n-TYPE DOPED GRADED AlGaN LAYER
44

FIG. 7